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Associations of Very High Energy Gamma-Ray Sources Discovered by H.E.S.S. with Pulsar Wind Nebulae

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Abstract The H.E.S.S. array of imaging Cherenkov telescopes has discovered a number of previously unknown γ-ray sources in the very high energy (VHE) domain above 100 GeV. The good angular resolution of H.E.S.S. ($\sim 0.1^\circ$ per event), as well as its sensitivity (a few percent of the Crab Nebula flux) and wide 5° field of view, allow a much better constrained search for counterparts in comparison to previous instruments. In several cases, the association of the VHE sources revealed by H.E.S.S. with pulsar wind nebulae (PWNe) is supported by a combination of positional and morphological evidence, multi-wavelength observations, and plausible PWN model parameters. These include the plerions in the composite supernova remnants G 0.9+0.1 and MSH 15–52, the recently discovered Vela X nebula, two new sources in the Kookaburra complex, and the association of HESS J1825–137 with PSR B1823–13. The properties of these better-established associations are reviewed. A number of other sources discovered by H.E.S.S. are located near high spin-down power pulsars, but the evidence for association is less complete. These possible associations are also discussed, in the context of the available multi-wavelength data and plausible PWN scenarios.

Keywords gamma rays: observations · pulsars · nebulae

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1 Introduction

The High Energy Stereoscopic System (H.E.S.S.) is an array of four imaging Cherenkov telescopes designed to study astrophysical gamma-rays in the energy domain between about 100 GeV and several tens of TeV. Its wide field of view and unprecedented sensitivity in this energy range have allowed the discovery of a large number of new very high energy (VHE) gamma-ray sources. Several of these are associated with pulsar wind nebulae (PWNe); they will be individually reviewed in section 2, and their general properties discussed. Section 3 will then examine the criteria for establishing such PWN associations, and discuss individual possible PWN counterparts for unidentified H.E.S.S. sources.

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2 "Established" VHE Pulsar Wind Nebulae

2.1 The Crab Nebula

The "standard candle" of very high energy (VHE) gamma-ray astronomy will serve to introduce the emission mechanisms at play in pulsar wind nebulae (PWNe). The Crab Nebula is a bright source of strongly polarised, non-thermal radiation across most of the electromagnetic spectrum. This emission, from the radio domain up to high-energy gamma-rays below 1 GeV, is generally interpreted as synchrotron radiation from relativistic electrons and positrons created and accelerated by the central pulsar.

The higher-energy emission component observed in VHE gamma-rays, and by *EGRET* as unpulsed emission above 1 GeV, is conventionally interpreted as inverse Compton (IC) scattering by the same accelerated electrons and positrons. Target photons for the scattering process include the cosmic microwave background (CMB), interstellar dust and stellar emission, and at least in the case of the Crab, the synchrotron photons themselves. Hadronic emission models have also been proposed for VHE emission from plerions (see [1,2]); in the present review, however, we will restrict ourselves to the more conservative leptonic models consisting of synchrotron and IC emission components.

Observations of the Crab Nebula with H.E.S.S. have revealed clear evidence for steepening at high energies of the VHE gamma-ray spectrum, which can be described by a power law of photon index $\Gamma = 2.39 \pm 0.03_{\rm stat}$ with an exponential cutoff energy $E_{\rm c} = 14.3 \pm 2.1_{\rm stat}$ TeV [3]. Such spectral curvature is consistent with expectations from model calculations of the IC emission spectrum.

2.2 VHE plerion in the composite SNR G 0.9+0.1

The Crab Nebula is the prototype of a purely *plerionic* supernova remnant (SNR), exhibiting a centre-filled morphology and strongly polarised, non-thermal emission, properties which are characteristic of PWNe. The Galactic SNR G 0.9+0.1 is of the more general *composite* type, in which such a plerion is found inside the shell of emission due to the supernova blast wave [4]. The composite morphology of G 0.9+0.1 is evident in the radio domain, and X-ray observations confirmed the non-thermal nature of the plerionic emission component. The pulsar thought to power this PWN has however not been detected up to now, presumably because its beaming is unfavourable.

VHE gamma-ray emission from G 0.9+0.1 was discovered in deep H.E.S.S. observations of the Galactic Centre region [5]. The observed gamma-ray excess is well described as a point source at a position consistent with that of the plerion; given the precise point spread function of H.E.S.S., an upper limit of $1.3'$ on the (assumed Gaussian) source extension was derived. This argues for the plerion rather than the shell as the counterpart of the VHE source. The available radio, X-ray and VHE gamma-ray spectral data are well described by a simple leptonic model, with a magnetic field inside the plerion of $6\,\mu$G, close to the equipartition value. The dominant IC target photon component in this model is from stellar photons rather than the CMB, as expected for a source located in the central regions of the Galaxy.

2.3 The nebula of PSR B1509–58 in MSH 15–5*2*

The composite SNR MSH 15–5*2*, also known as G 320.4–1.2, comprises an X-ray and radio-emitting shell which encloses a bright, non-thermal X-ray nebula around the young pulsar B1509–58 (see e.g. [6]). The good angular resolution of H.E.S.S. allowed the discovery of an extended source of VHE gamma-rays in this SNR, with a morphology similar to that of the non-thermal X-ray nebula [7]. This morphological correspondence, and the fact that the available spectral data can be described by a simple leptonic model with a plerion magnetic field value of $\sim 17\,\mu$G, motivate the identification of the PWN as the source of the VHE emission.

This H.E.S.S. discovery provided the first illustration of the potential for VHE gamma-ray morphological studies of PWNe. The synchrotron emission observed at lower frequencies reflects the spatial distribution of a combination of the accelerated electron density and the magnetic field strength, and the latter can in general be quite non-uniform in PWNe. By contrast, in a typical IC emission scenario the target photons are approximately uniformly distributed on the scale of the SNR, so that the VHE emission directly reflects the spatial distribution of the high-energy electrons. In the case of MSH 15–5*2*, the observed VHE morphology confirms that these electrons are predominantly distributed along a NW-SE direction, which is thought to reflect the rotation axis of the pulsar.

2.4 The Vela X plerionic nebula

The Vela SNR is a large (diameter $\sim 8^\circ$), nearby (distance $D \approx 290$ pc) composite remnant. It contains a radio-emitting plerionic nebula, Vela X, powered by the young and energetic Vela pulsar, PSR B0833–45. Observations of this region with H.E.S.S. revealed a very extended source of VHE gamma-rays centered to the south of the pulsar [8], overlapping a diffuse hard X-ray emission feature first detected with *ROSAT* [9] and aligned with a bright radio filament within the plerion.

In this PWN, the radio, X-ray and VHE gamma-ray emission regions are all markedly offset from the pulsar position. This may be due to the supernova explosion occurring in an inhomogeneous medium, and the resulting asymmetric reverse shock displacing the PWN in the direction away from the higher density medium [10]. Such an offset may be typical of older PWNe; the Vela pulsar has a spin-down age of 11 kyr, significantly older than that of the Crab (1.2 kyr) or B1509–58 (1.7 kyr).

The VHE gamma-ray spectrum of this source significantly steepens with increasing energy, and can be described by a power law of photon index $\Gamma = 1.45 \pm 0.09_{\rm stat} \pm 0.2_{\rm sys}$ with an exponential cutoff energy $13.8 \pm 2.3_{\rm stat} \pm 4.1_{\rm sys}$ TeV; this constitutes the first clear measurement of a peak in the spectral energy distribution at VHE energies [8]. Assuming the CMB is the main target photon component for IC scattering in the outer regions of the Galaxy, a total energy of $\sim 2 \times 10^{45}$ erg in non-thermal electrons between 5 TeV and 100 TeV could be deduced. These results demonstrate how VHE observations of IC emission allow direct inference of the *spatial* and *spectral* distribution of non-thermal electrons in a PWN.

2.5 Two new VHE sources in the Kookaburra

Although the distribution of target photons for IC emission it not uniform in the Galaxy, it varies relatively smoothly in contrast to the distribution of target material for hadronic gamma-ray emission processes. Moreover, the CMB provides a minimum target photon density which is uniformly distributed. Sensitive VHE gamma-ray observations should thus reveal any sufficiently intense source of high-energy electrons in the Galaxy, again in contrast to sources of high-energy hadrons, for which the presence of dense target material is also a necessary condition for detectability. The survey of the Galactic plane undertaken with H.E.S.S. thus has a strong potential for detecting energetic PWNe.

A survey of the Galactic plane performed with H.E.S.S. in 2005, in the Galactic longitude range $300^\circ < \ell < 330^\circ$, allowed the discovery of two new VHE sources located in the Kookaburra complex of radio and X-ray emission [11]. The stronger of the two VHE sources, HESS J1420–607, is most plausibly associated with the radio and X-ray nebula of the energetic pulsar PSR J1420–6048. The second source, HESS J1418–609, is similarly associated with radio and X-ray emission exhibiting the properties of PWN, the so-called

Rabbit, though a pulsar has so far not been clearly detected in this object [12].

In both sources, the VHE emission has a large spatial extent and is significantly offset from the pulsar position, which may be due to "crushing" of the PWN by the SNR reverse shock as hypothesised in the case of Vela X, or perhaps to the effects of rapid motion of the pulsar through the surrounding medium [11]. Both PWNe have been proposed as possible counterparts of an unidentified *EGRET* source coincident with the Kookaburra complex. The clear separation by H.E.S.S. of two VHE sources, coincident with each of the two PWNe, illustrates the advantages of good angular resolution in identifying the counterparts of gamma-ray sources.

2.6 HESS J1825–137 as the nebula of PSR B1823–13

HESS J1825–137 is a strong VHE source discovered in the first H.E.S.S. survey of the Galactic plane [13]. PSR B1823–13, a pulsar with properties similar to that of Vela, lies at its Northern edge, and exhibits an asymmetric X-ray nebula extending in the direction of the centre of the VHE source [14]. The detected diffuse X-ray emission only extends over $\sim 5'$, however, much smaller than the size of the VHE source. In contrast to the previously discussed sources, there is no good morphological match of HESS J1825–137 with emission detected at other wavelengths.

Morphological studies of HESS J1825–137 in the VHE gamma-ray domain have nonetheless yielded compelling evidence for its association with PSR B1823–13. In particular, the VHE emission has an asymmetric profile with a sharp peak immediately South of the pulsar position; the shape of this profile is similar to that of the X-ray nebula, but the VHE profile extends over a much larger scale [15]. More importantly, deeper H.E.S.S. observations have revealed the energy-dependent morphology of HESS J1825–137, marking the first time such an effect is detected in VHE gamma-rays. This manifests itself as a steepening of the power-law spectral index with increasing distance from PSR B1823–13, as would be expected from radiative losses of high-energy electrons injected by the pulsar [16]. These losses could also account for the fact that the PWN appears larger in VHE gamma-rays than in X-rays, as in a leptonic scenario the latter are emitted by higher-energy electrons.

3 VHE Pulsar Wind Nebula Candidates

3.1 Association criteria

A total of seven fairly well-established associations of VHE gamma-ray sources with PWNe have been reviewed in section 2. To these might be added the VHE emission associated with PSR B1259–63 [17]. This object is in a different class from the other PWNe and candidate PWNe discussed above and below, however, in that it is dominated by the interaction with its binary companion, as evidenced by its orbital variability; it will thus not be considered further here.

Table 1 Apparent efficiencies for "established" associations

VHE source	$F_{0.3-30}$ [a]	PSR name	ε
Crab nebula	1.7×10^{-10}	B0531+21	0.02%
MSH 15–52	3.3×10^{-11}	B1509–58	0.4%
Vela X	9×10^{-11}	B0833–45	0.01%
HESS J1420–607	2.2×10^{-11}	J1420–6048	0.8%
HESS J1825–137	1.1×10^{-10}	B1823–13	7%

[a] in units of erg cm^{-2} s^{-1}

For six of the VHE sources discussed in section 2, the association rests on a positional and morphological match to a PWN known at lower energies. When this is not the case, i.e. for HESS J1825–137, an alternative criterion is morphological and spectral evidence in the VHE gamma-ray domain for association with a known pulsar, and consistent data at other wavelengths. In all cases, another necessary criterion is a physically plausible spectral model which is consistent with the available multi-wavelength (MWL) data on the object. In this section we will examine other candidate associations, for which the above criteria are not currently all fulfilled with the available MWL and VHE data.

3.2 Pulsar energetics

When considering the association of a VHE source with the nebula of a known pulsar, an additional criterion is the apparent efficiency for VHE gamma-ray emission, given the pulsar's current spin-down luminosity $\dot{E}$. The comparison assumes that the VHE source is located at the pulsar distance D, generally determined from the radio dispersion measure. For definiteness, we use the VHE energy flux $F_{0.3-30}$ integrated over the the energy range 0.3–30 TeV. This is roughly representative of the H.E.S.S. spectral analysis range, although the energy threshold for individual sources depends on the observation zenith angle, and the upper limit depends on photon statistics. The apparent efficiency ε is then defined as $\varepsilon \equiv \left(4\pi D^2 F_{0.3-30}\right)/\dot{E}$.

Table 1 list the VHE energy fluxes and apparent efficiencies for the five well-established VHE PWNe in which the pulsar has been detected and timed. The fluxes $F_{0.3-30}$ were obtained by integration of the best-fit spectral model as given in the references listed in section 2. The pulsar parameters $\dot{E}$ and D were obtained from the ATNF Pulsar Catalogue [18], version 1.25, using the NE2001 model of the Galactic free electron distribution for the distance [19].

The apparent efficiency reflects the true efficiency only to the extent that the emitting particles' lifetimes are short compared with the evolutionary time scale of the PWN. In general the VHE-emitting electrons may have been injected in the early phases of the PWN evolution, when the pulsar's $\dot{E}$ was larger, so that the apparent efficiency is an overestimate of the true efficiency; this appears to be the case in particular for HESS J1825–137 [16]. Nonetheless, associations for which the required efficiency approaches 100% may be considered questionable, and those for which it far exceeds this can generally be ruled out as implausible.

3.3 Possible associations with known pulsars

In addition to HESS J1825–137, two other VHE sources discovered in the initial H.E.S.S. survey of the Galactic plane may be associated with energetic pulsars [13]. Located near the edge of the bright source HESS J1616–508 is PSR J1617–5055, an X-ray emitting young pulsar with a period of 69 ms and a spin-down luminosity $\dot{E} = 1.6 \times 10^{37}$ erg/s. Although its association with the VHE source is energetically plausible, the putative wind nebula of this pulsar has not been detected at other wavelengths.

One of the brightest and largest sources discovered in the Galactic plane survey, HESS J1804–216, contains the young and energetic pulsar B1800–21, with spin-down luminosity $\dot{E} = 2.2 \times 10^{36}$ erg/s. As in the previous case, an association is energetically plausible, but no coincident PWN has been detected at other wavelengths. Alternatively, the H.E.S.S. source could be associated with part of the shell-type SNR G 8.7–0.1 [20].

Although HESS J1303–631, the first unidentified source discovered by H.E.S.S., has no established counterpart, it does coincide with the energetic pulsar J1301–6305, with spin-down luminosity $\dot{E} = 1.7 \times 10^{36}$ erg/s. Its catalogued distance using the Galactic free electron model of Taylor and Cordes [21] was $D = 15.8$ kpc, which required a very high efficiency of order 40% to power the VHE source [22]. The more recent NE2001 model, however, implies a distance of only $D = 6.65$ kpc, making the apparent efficiency comparable with that for HESS J1825–137 (see Table 2).

One additional possible association is with HESS J1702–420 discovered in the Galactic plane survey. The nearby pulsar J1702–4128 would require a high but not impossible efficiency to power the entire H.E.S.S source. It is located near the tip of a tail-like extension from HESS J1702–420. Although this tail was not statistically significant in the original survey data [20], additional H.E.S.S. observations have since increased its significance. The offset of PSR J1702–4128 from the core of HESS J1702–420 is large, making an association less likely, but it may be that only part of the H.E.S.S. source is associated with the nebula of PSR J1702–4182. If such an association were confirmed, with a spin-down age of 55 kyr and luminosity $\dot{E} = 3.4 \times 10^{35}$ erg/s this would be the oldest and least energetic pulsar yet found to have a VHE-emitting wind nebula.

Table 2 summarises the VHE energy fluxes and required efficiencies for these candidate associations; the numbers were derived in the same manner as in Table 1. In all cases the pulsar is significantly offset from the centre of the VHE source, but as was seen in section 2, this would seem to be typical of older VHE PWNe. Deeper MWL or VHE observations would be necessary in order to establish any of these candidate associations.

Table 2 Required efficiencies for candidate associations

VHE source	$F_{0.3-30}$ [a]	PSR name	ε
HESS J1616–508	3.7×10^{-11}	J1617–5055	1.3%
HESS J1804–216	2.9×10^{-11}	B1800–21	2.4%
HESS J1303–631	2.3×10^{-11}	J1301–6305	7%
HESS J1702–420	1.4×10^{-11}	J1702–4128	11%

[a] in units of erg cm^{-2} s^{-1}

3.4 Possible VHE PWNe without detected pulsars

The example of G 0.9+0.1 shows that H.E.S.S.-discovered sources can be associated with PWNe even if the corresponding pulsar has not been detected, in particular when the VHE source is coincident with a composite SNR. Another possible such association is with HESS J1813–178; this relatively compact VHE source was discovered in the Galactic plane survey [13], and was subsequently found to be coincident with a shell-type radio SNR, G 12.82–0.02 [23,24], and a bright, non-thermal, hard X-ray source [23,25]. The angular resolution of H.E.S.S. or of the available X-ray data could however not discriminate between the shell and a possible embedded PWN as the source of the respective emission. A recent *XMM-Newton* observation of this region shows evidence for a PWN origin of the X-ray emission, suggesting a composite nature for G 12.82–0.02 and the possibility of a PWN origin for the VHE emission [26].

Another source discovered in the Galactic plane survey is HESS J1834–087, which is positionally coincident with the radio SNR G 23.3–0.3, also known as W41. The VHE source extension appears to be smaller than the radius of the shell, and its position coincides with a region of enhanced radio emission near the centre of the shell [20]. This suggests the intriguing possibility that W41 might be a composite SNR, and the VHE emission might originate in a central plerion; more MWL observations of this SNR are needed to support such a scenario, however. An alternative possibility is that the VHE emission is due to hadronic processes and originates in a large molecular cloud associated with W41, which is in good positional coincidence with the VHE source [27].

As a final example, one of the potential counterparts suggested for the Galactic survey source HESS J1634–472 [20] was the radio SNR candidate G 337.2+0.1, coincident with an X-ray source detected by *ASCA* [28]. A recent *XMM-Newton* observation of this region shows evidence for a PWN origin of the X-ray emission [29] and raises the possibility of a PWN association for the VHE emission. The relatively small angular size of this candidate radio and X-ray PWN compared with that of HESS J1634–472, and its location near the edge of the VHE excess, nonetheless make an association with the whole of the VHE source unlikely.

4 Summary and Prospects

Of the VHE gamma-ray sources detected by H.E.S.S., seven have fairly well-established PWN counterparts, not including the VHE emission associated with PSR B1259–63. These currently constitute the most numerous class of identified Galactic VHE gamma-ray sources. Several of these VHE-emitting PWNe exhibit a large physical extent and are significantly offset from the pulsar position; one possible explanation is that these are older PWNe, strongly affected by the passage of an asymmetric reverse shock in the parent SNR.

In a leptonic interpretation of the VHE emission, the target photons for IC scattering have an approximately known and uniform density in individual PWNe, which allows direct inference of the *spectral* and *spatial* distribution of the energetic electrons, in contrast to observations of synchrotron emission at lower energies. VHE gamma-ray astronomy thus provides a new, independent observational window into the physics of PWNe.

Given smoothly varying Galactic target photon densities, and the uniform target density provided by the Cosmic Microwave Background, a survey in VHE gamma-rays should reveal all sufficiently intense Galactic sources of high-energy electrons. Four more VHE sources discovered by H.E.S.S. may be associated with known energetic pulsars, and three additional such sources are coincident with possible PWNe in which the pulsar has not been detected. More observations of these sources in VHE gamma-rays and at other wavelengths are necessary to investigate the possibility of these associations. PWNe may yet prove to constitute the fastest-growing class of identified Galactic gamma-ray sources.

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